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## TRANSPORTABLE SEISMIC DISCRIMINANTS

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## ABSTRACT

This research addresses the issue of discriminant transportability, that is, the development of discriminants which can be applied to events in a variety of geographic areas. The failure of discriminants to work for events in new areas of study is most often attributed to the effects of changes in the propagation path ( $Q$ , phase blockage, scattering, focusing/defocusing, etc.). An additional factor is the instability of spectral ratio measurements. The spectra of  $Pn$  and  $Lg$  waves for small explosions often exhibit spectral nulls due to the time-delayed multiple shots. Often these spectral nulls occur at slightly different frequencies, contributing to artificial maxima and minima of the  $Lg/Pn$  spectral ratio. In our approach, we deconvolve the source effects separately for  $Lg$  and  $Pn$  before the spectral ratio is computed. This is accomplished by detrending the array averaged log-spectra and then computing a source time function based on the spectral nulls. We use both the deconvolved spectral ratio and the derived source time function for event identification. This procedure has been tested on a number of Ground Truth Databases which include events from Scandinavia, central Europe, Spain, and the Middle East.

## CTBT RELEVANCE

Transportability of discriminants is an important issue in the monitoring of a global CTBT because the events which generate the most interest will likely be those which occur in geographic areas which have yet to be studied with seismic methods. Additionally, if the scatter in discriminants can be reduced, their reliability for source identification even in areas already studied should improve.

## KEY WORDS

Discrimination, mining, explosions, signal processing, discriminant transportability, ground-truth databases

## Background

For over ten years it has been known that there are observable differences in the regional phases  $P_n$ ,  $S_n$ , and  $L_g$  for earthquakes and explosion sources (e.g. Dysart and Pulli (1987), Baumgardt and Ziegler (1988), Hedlin *et al.* (1990)). These differences were noted in the (relatively) high-frequency band of the data, using events recorded at the newly installed NORESS, ARCESS, and FINESA arrays. Specifically, it was noted that the  $L_g/P_n$  and  $S_n/P_n$  spectral ratios above 10 Hz provided excellent discrimination capability. Research then focused on a variety of methods to parameterize and process these observed differences, including statistical methods (Shumway, 1996), neural network methods (Dysart and Pulli, 1990), and fuzzy logic (Serenio and Wahl, 1993).

However, when these discriminants were applied to events in new areas of interest, their ability to identify source types was shown to be inferior when compared to events from the original source area. In hindsight this was not unexpected, given the area-to-area variation in propagation effects which can change the spectral content of the regional phases. Some of these effects, such as anelastic attenuation, can be independently measured and modeled for application to the observed spectra. Other effects, such as  $L_g$  blockage and the focusing/defocusing of regional phases due to velocity perturbations, are more difficult to correct. Scattering also contributes to spectral variation (Dainty, 1996), although recent developments in the measurement of scattered waves (coda) show promise for source identification (Mayeda and Walter, 1996).

An additional consideration is the actual comparison of the  $P_n$ ,  $S_n$ , and  $L_g$  phase spectra. Spectral ratios are typically used for spectral comparison and these formed the basis of our early studies. To parameterize the spectral ratios, we computed the mean values of  $L_g/P_n$  and  $S_n/P_n$  over a variety of frequency bands: 0-20 Hz to characterize the broadband spectra as well as 2-5 Hz, 5-10 Hz, and 10-20 Hz. A closer examination of this calculation illustrates the difficulty of the estimation. *Fig.1* shows the  $L_g$  and  $P_n$  spectra for an explosion at the Koashva Nostoch apatite mine in the Apatity area. The  $L_g$  spectrum peaks around 2 Hz, then quickly decays by a factor of

10, after which there is a smooth decay with frequency. The  $P_n$  spectrum however shows evidence of spectral scalloping as is often seen in quarry explosions. This is presumably due to ripple firing (if the firing pattern is delayed by enough time to appear in the pass band of the data) or the total length of the firing pattern. When we calculate the  $Lg/P_n$  spectral ratio, these peaks and troughs of the spectra result in an estimate which shows simply artifacts of the spectral ratio and not a true comparison of the relationship of the spectral energy in each phase.

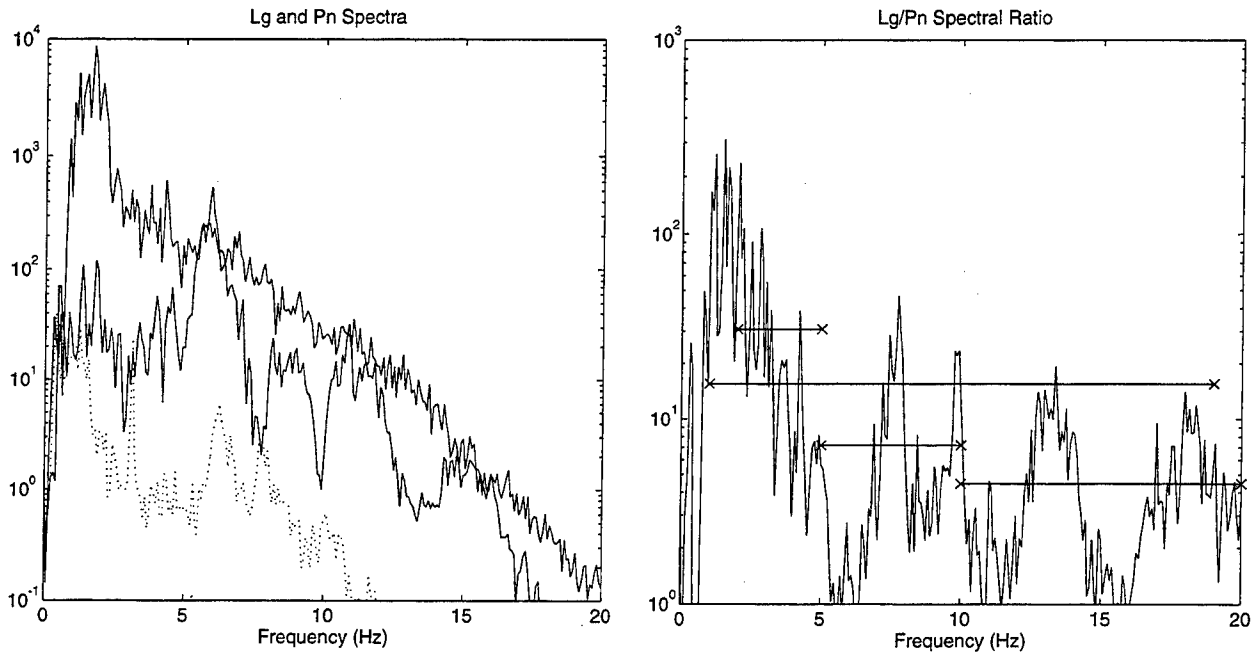


Figure 1.  $Lg$  and  $P_n$  spectra (left) as well as  $Lg/P_n$  spectral ratio (right) for an explosion at the Koashva Nostoch apatite mine in the Apatity area (GTDB event number 2066). The spectral ratio has been parameterized as mean values across the entire band as well as from 2-5 Hz, 5-10 Hz, and 10-20 Hz. In this case, the parameterization is clearly not representative of the data.

## Approach

In our approach, we deconvolve the source effects separately for  $Lg$  and  $P_n$  before the spectral ratio is computed. This is accomplished by first detrending the array averaged log-spectra of  $Lg$  and  $P_n$ , then computing a source time function based on the spectral nulls. This source time function is then deconvolved from the observed spectra in the frequency domain. The scatter in the



resulting spectral ratio parameterizations is then reduced. Additionally, the deconvolved spectral ratios can be used in conjunction with the derived source time function as a combined discriminant. This procedure has been tested on a number of Ground Truth Databases which include events from Scandinavia, Spain, and the Middle East.

## Software and Data Processing

Software used during this research effort has been written in the MATLAB® technical computing environment. The software consists of scripts or functions (so-called *m-files*) which call the built-in MATLAB® routines to perform basic vector and matrix computations. These scripts can be linked to compiled C or FORTRAN objects, or can be translated to ANSI C using a supplied compiler. Toolboxes, which combine numerous *m-files*, are also available which perform groups of functions, such as signal processing, image processing, and neural computing. This computing environment was chosen to take advantage of signal processing routines already developed for other projects, and because the binary data files (*mat-files*) and ASCII *m-files* can be moved from platform-to-platform (UNIX, PC, Macintosh) without translation.

The starting point is a CMR Version 3.0 database (*.wfdisc*, *.origin*, and *.w* files; see Anderson *et al*, 1990). The C-program *css2matlab* reads a user-specified *.wfdisc* file and generates *mat-files* for each *.wfdisc* entry with file names *station\_channel.mat* (e.g. *ARA0\_sz.mat*). Each *mat-file* contains variables with names corresponding to those in the CMR Version 3.0 definition, as well as other comments which are used by subsequent plotting routines. At this point, the programs *gram.m* and *zoom.m* are used to display a single channel of data and select windows for the noise, *Pn*, *Sn*, and *Lg* phases. The program *extract\_arcess.m* (as well as programs for the NORESS, GERESS, FINESA, and ILPA arrays) are used to extract the waveform segments and produce matrix variables of the phase waveforms across each array. For the regional data of interest to this project, waveform segments consist of 512-points for each channel, corresponding to 12.8 seconds for the typical 40 samples/second digitization. Once the waveforms have been extracted, *event* files (e.g. *e2002.mat*) are created which contain all of the relevant information,

including that from the *.origin* file if available. Event names correspond to the *.wfdisc* prefix name in order to remain consistent with the Ground-Truth Database convention (Grant *et. al*, 1993).

Signal processing is accomplished with a variety of developed *m-files* which typically consist of four versions: *compute*, *plot*, *process*, and *hardcopy*. For example, there is *compute\_spectra.m*, *plot\_spectra.m*, *process\_spectra.m*, and *hardcopy\_spectra.m*. The *compute* version performs the actual calculation, the *plot* version plots the results, the *process* version batches all *event* files for the *compute* version and saves the result to each *event* file, and the *hardcopy* version batches all plots to a specified printer. *m-files* have been developed to perform a variety of these signal processing functions, including spectra, power spectral density, cepstra, coherence, cross-spectra, multiple-filter analysis, spectral ratios, and beamforming, as well as three-component analysis.

## Databases Examined

Our earlier studies of regional seismic event identification utilized the parameterization of the *Pn*, *Sn*, and *Lg* spectra discussed above (mean values over broad and narrow bands). Waveform windows of the regional phases were not saved as part of the effort, just the parameterizations of the spectra. In order to address this new research, we dearchived all of the old data and used the software described above to re-pick phase windows and create event files consisting of the waveform segments of pre-event noise, *Pn*, *Sn*, and *Lg* phases. These databases include:

- NORESS events from 1985 - 1988, earthquakes & mining explosions
- Ground Truth Database 1: Vogtland earthquakes & explosions
- Ground Truth Database 2: Steigen earthquake swarm
- Ground Truth Database 8: Apatity mining-induced tremors
- Ground Truth Database 9: Apatity mine blasts
- Spanish Ground Truth Database: Alhucemas & Puertollano events

## Observations and Analysis

*Fig. 2* shows *Pn* recordings at the ARCESS array of six small explosions at the Apatity mining area. In each case the array data have been steered toward the source to illustrate the correlation of multiple arrivals in the *Pn* wave train. Note that for Events 2022, 2023, 2024, 2039, and 2046, the *Pn* wave consists of 2 or 3 distinct arrivals, whereas for Event 2045 the *Pn* arrival is a single pulse. Since these events are from the same area, this difference in arrival structure is likely a source effect, resulting from different firing patterns for each explosion at the quarry.

*Fig. 3* shows the corresponding spectra of *Pn*, *Lg*, and pre-event noise for these same mining explosions. Note that for event 2039 the spectral nulls for *Pn* and *Lg* waves occur at the same frequencies, but for event 2046 the spectral nulls are absent for *Lg*. *Fig. 4* shows the array averaged autocorrelations of *Pn* and *Lg*. Note that these autocorrelations indicate a source time function that is different for *Pn* versus *Lg*.

The objective of the deconvolution is to remove the effect of the multiple explosions while retaining the information from the individual shot. This can be accomplished in a number of ways. One way is to manually pick the peaks and troughs of the *Pn* and *Lg* spectra and sort the delays. The delay pattern is determined from either the inverse of the peak frequency of the inverse, or 2 times the trough frequency. A second way is to pre-whiten the observed spectra with a frequency-squared correction, threshold the spectra, inverse Fourier transform, and compare the results with the autocorrelation. A third way is to precompute the interference spectra for a wide range of possible source time functions (*Fig. 5*) and perform a pattern match between the models and the pre-whitened observed spectra. This is followed by an inverse Fourier transform and a comparison with the autocorrelation.

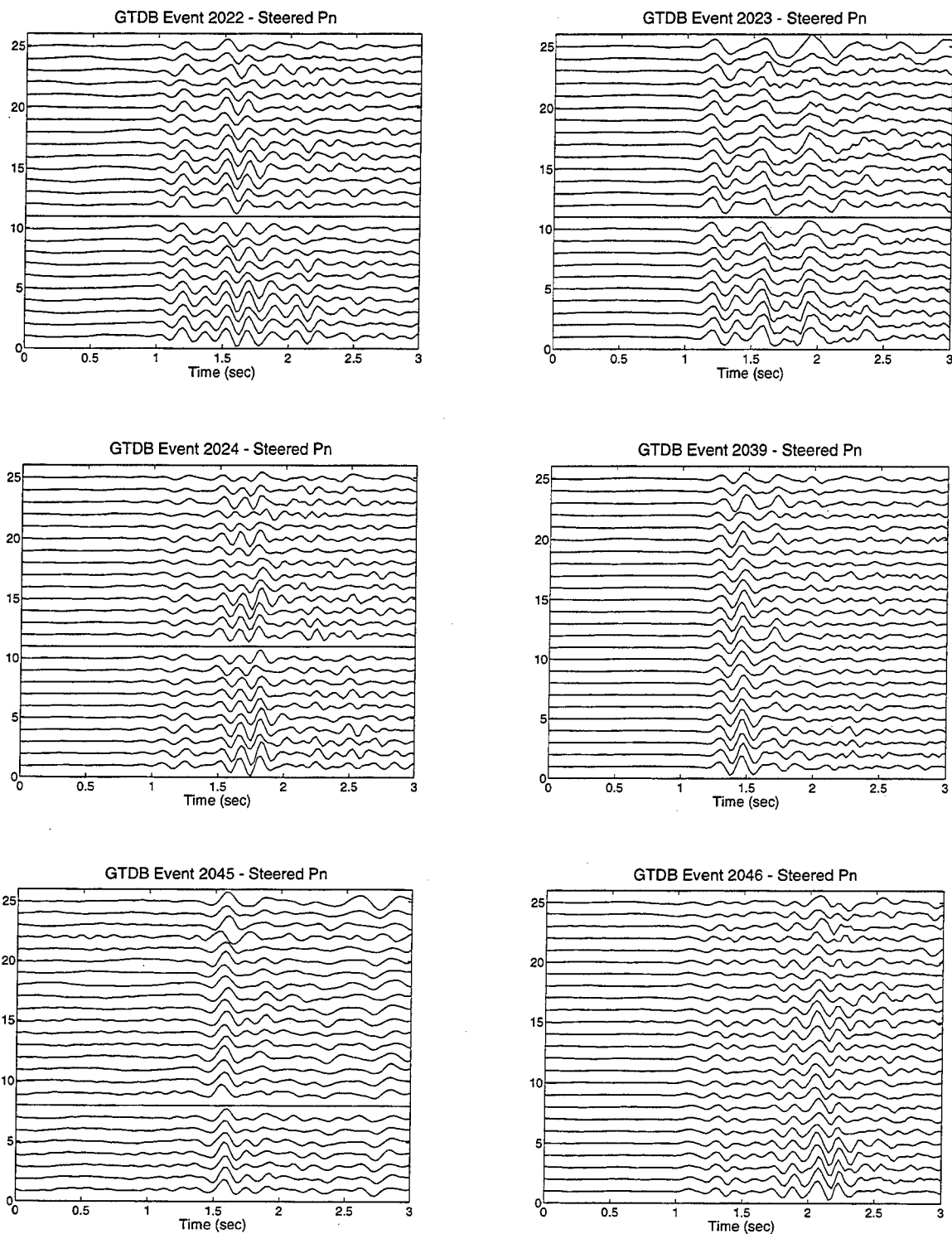


Figure 2. Steered  $P_n$  waveforms at ARCESS for six mining explosions at the Apatity area.

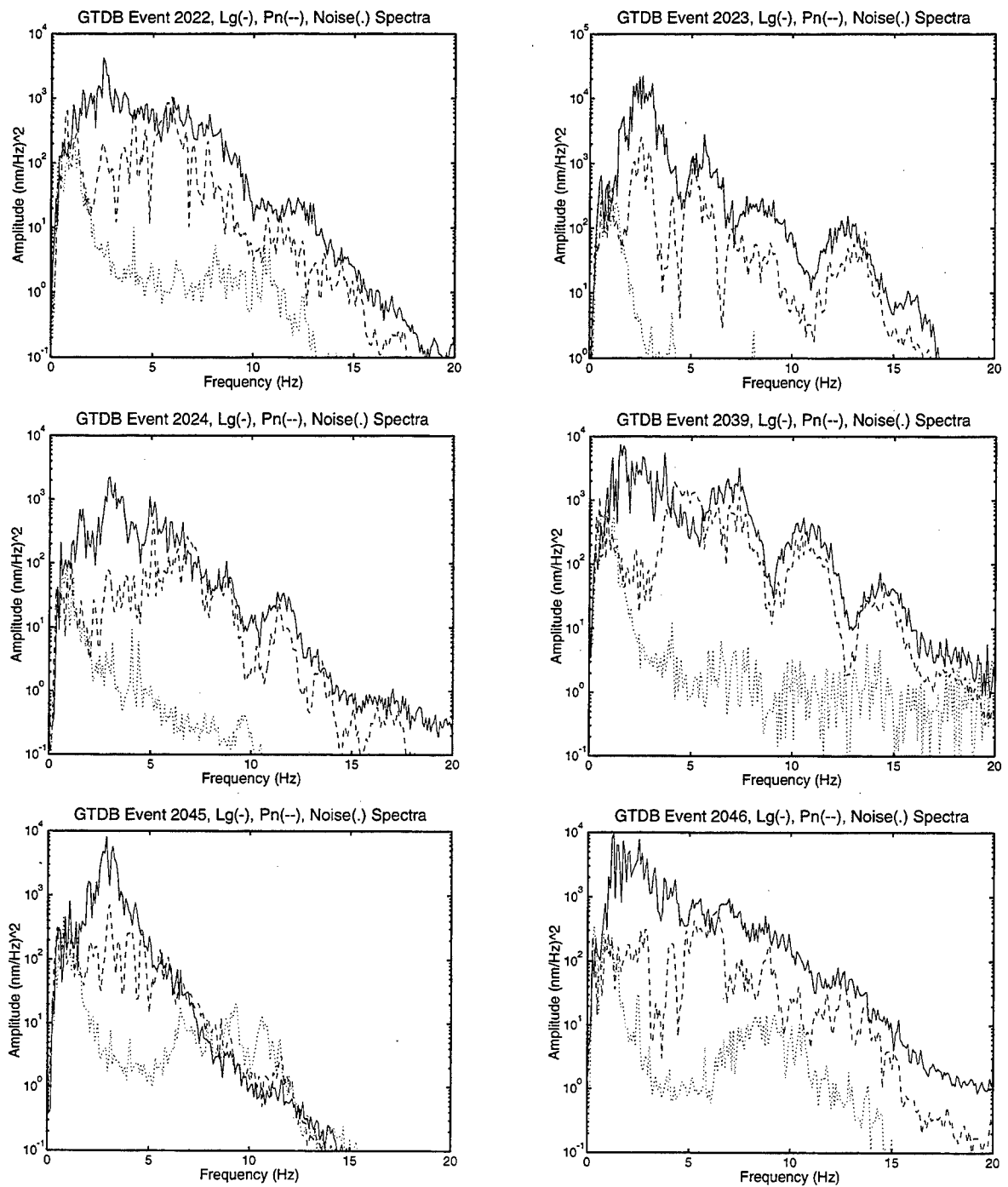


Figure 3. ARCESS array estimates of  $P_n$ ,  $L_g$ , and noise spectra for six mining explosions at Apatity.

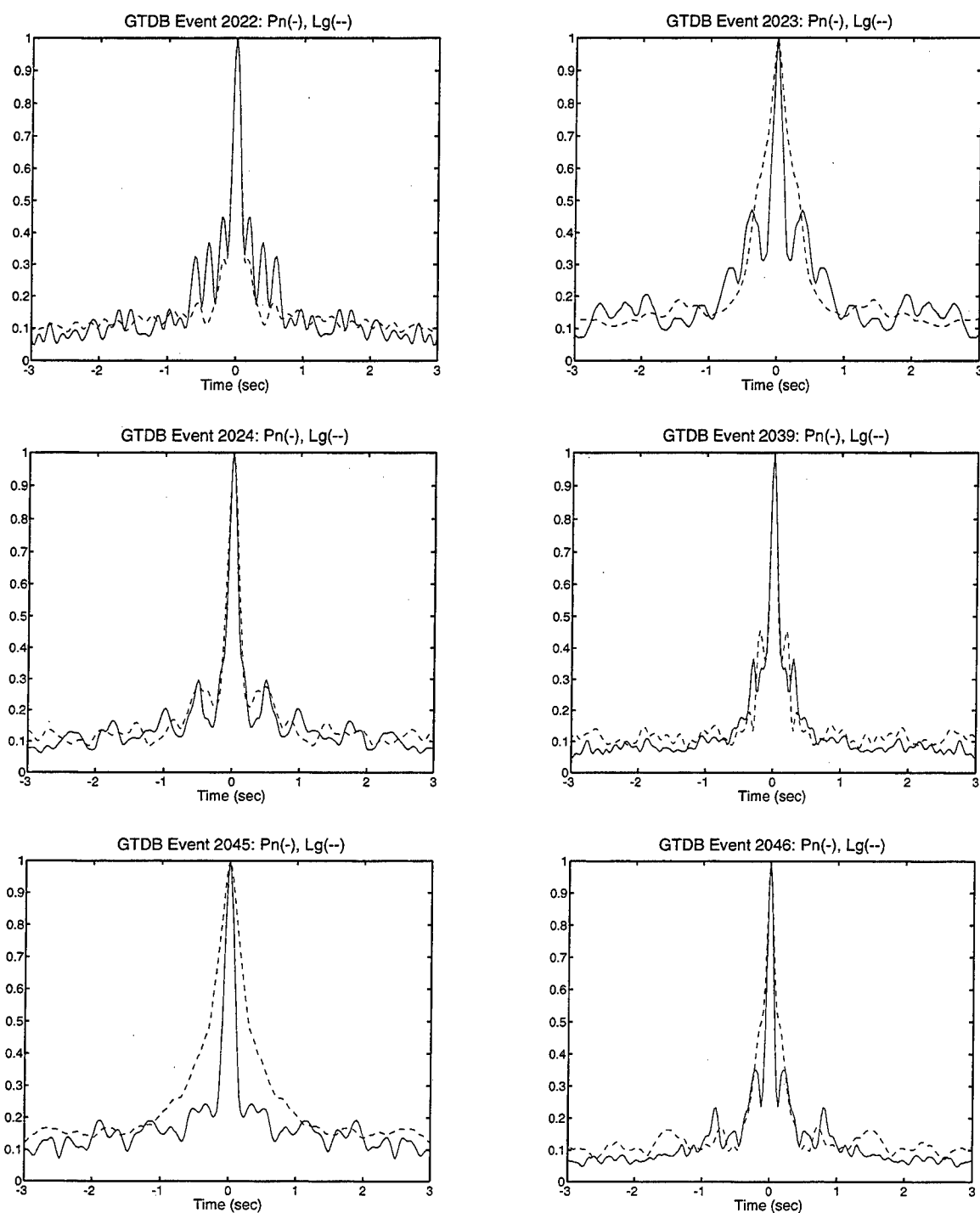


Figure 4. ARCESS array estimates of Pn and Lg autocorrelations for six mining explosions at Apatity.

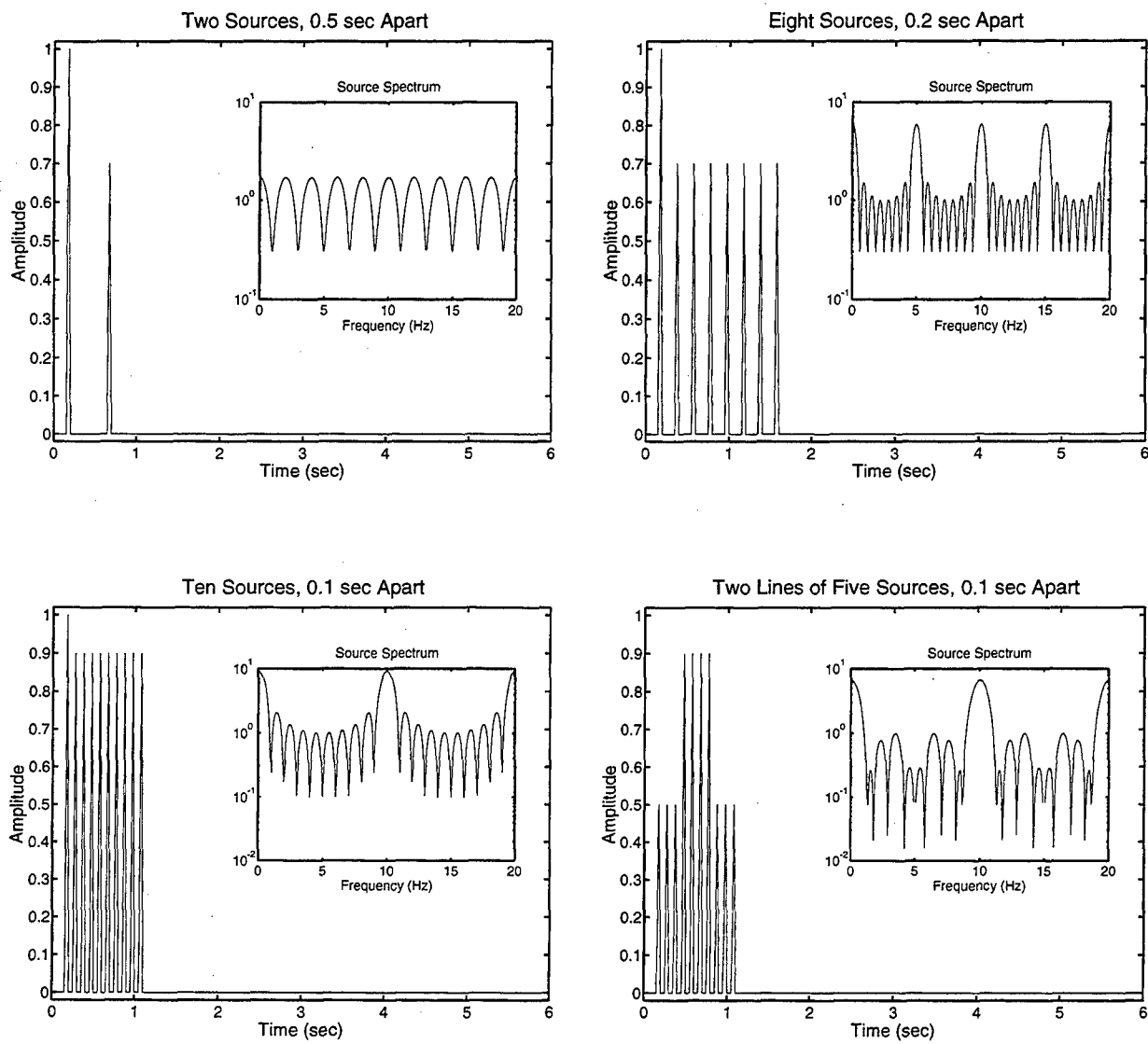


Figure 5. Model spectra of a quarry blast source consisting of multiple charges.

*Fig. 6* shows the resulting effect on the broadband  $Pn/Lg$  spectral ratios for 100 events recorded at the NORESS array. Source type was determined from a number of local bulletin sources as explained in Dysart and Pulli (1990). The upper figure shows the spectral ratios calculated without source deconvolution. Note that the scatter in this discriminant is large for explosions, since these events show the largest variation in source time function. Once this source time function is deconvolved from the spectra, the resulting spectral ratios show much less scatter.

### **Incorporation of Derived Source Time Function**

The source deconvolution just described essentially removes the information about the multiple nature of the source in order to derive the underlying single source spectral ratio. However, the multiple nature of the source is in itself an indicator of source type. So a valid question is whether or not we can combine this information for source identification.

*Fig. 7* shows the derived source time function durations for the 102 NORESS events analyzed in the previous section. The earthquakes in this data set have source time functions that range from zero (or the resolution of the data) to 0.5 seconds. The explosions have source time functions that range from zero to 1.8 seconds.

*Fig. 8* plots these derived source time functions versus the deconvolved broadband  $Pn/Lg$  spectral ratios. The use of these two parameters provides complete event type separation for this data set.

### **Extension to Other Ground Truth Databases**

The overall objective of this work has been the determination of so-called transportable seismic discriminants, and the approach has been to stabilize the most widely used seismic discriminant, the spectral ratio. At this point, we examine the use of this stabilized spectral ratio along with the derived source time function for events outside the area of initial study. This has



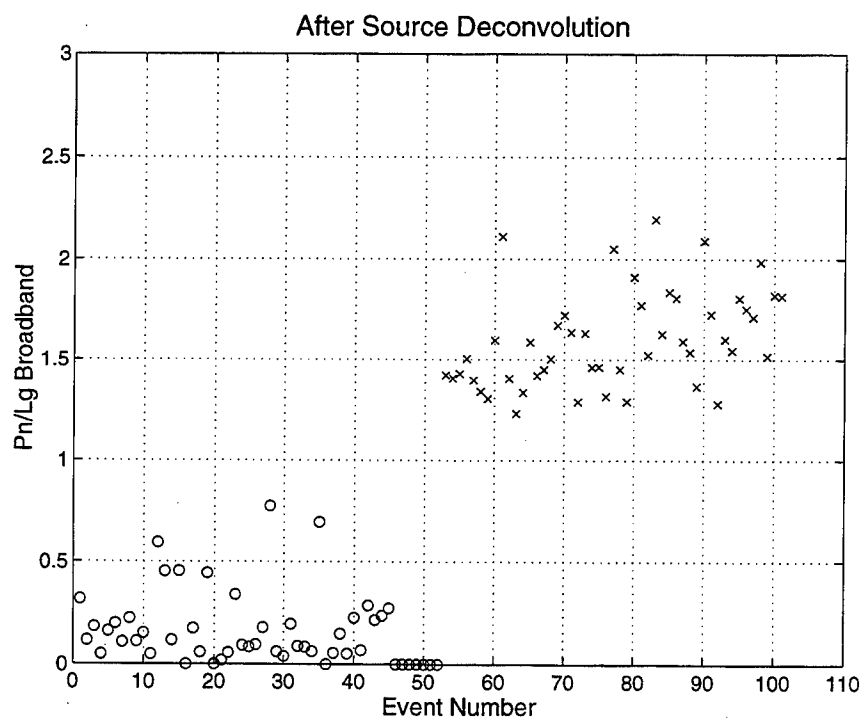
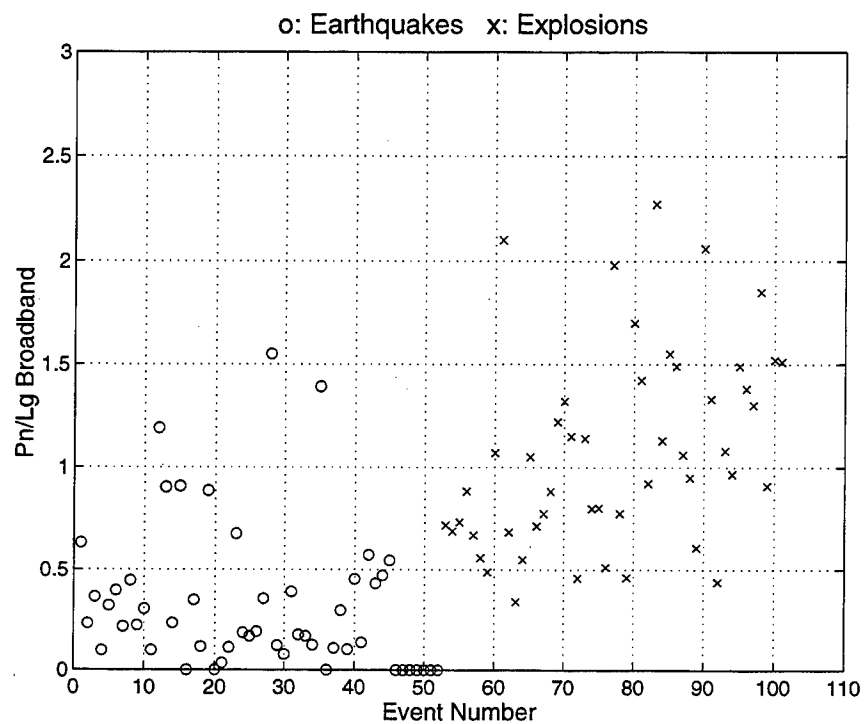


Figure 6. Broadband Pn/Lg spectral ratios at NORESS before (top) and after (bottom) deconvolution.

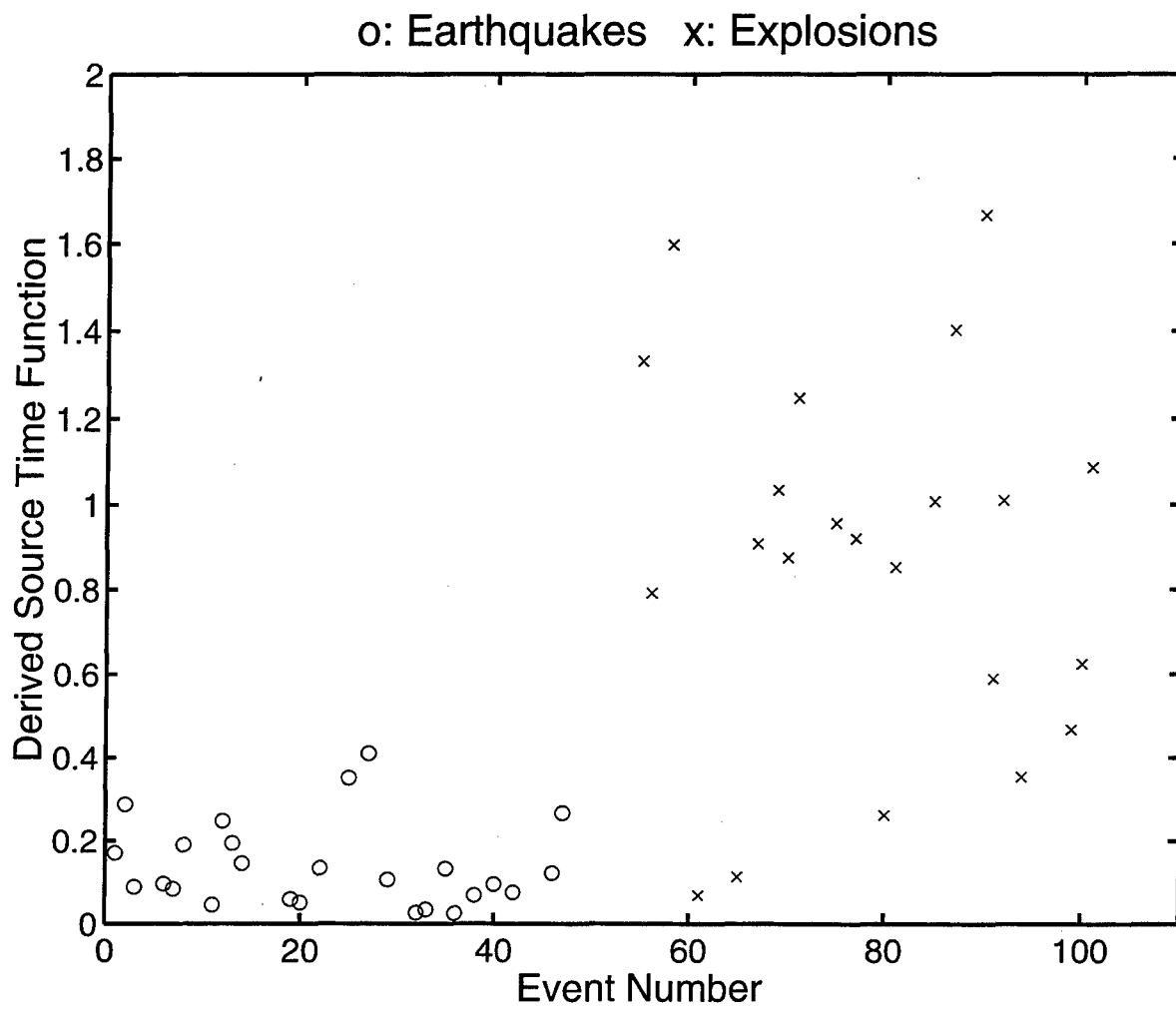


Figure 7. Derived source time function for earthquakes and explosions recorded at NORESS.

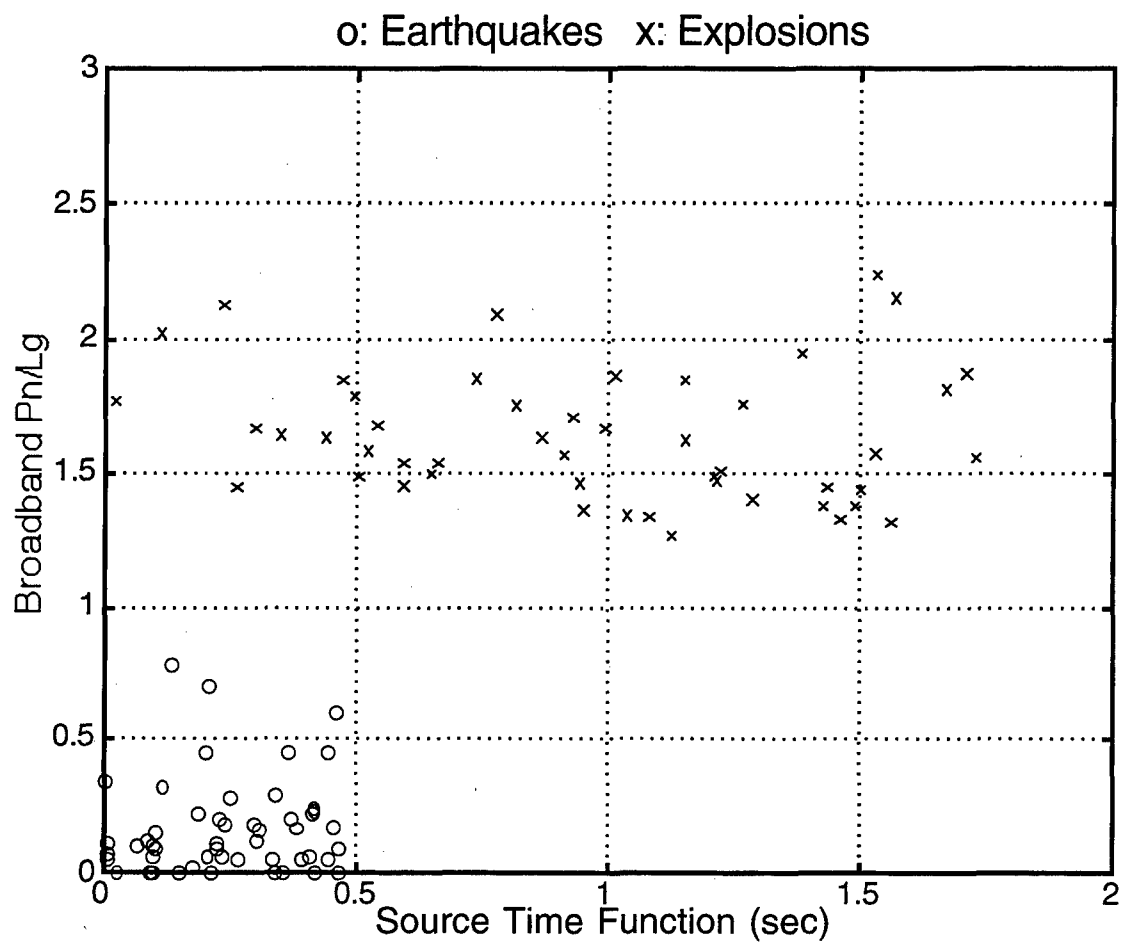


Figure 8. Broadband Pn/Lg spectral ratios after source deconvolution versus derived source time function for NORESS events.

involved the analysis of new Ground Truth Databases compiled as part of the sponsor's overall research program. For example, the Spanish Dataset includes recordings of mining explosions and earthquakes at the Sonseca Array, and we can use this array to examine whether or not the observation of multiple arrivals in the  $Pn$  wave train can be seen, as is often seen at the Scandinavian arrays. *Fig. 9* shows the steered  $Pn$  arrivals at the Sonseca array for four mining explosions in the Puertollano subset of the database. Although not as prominent as with mining explosions at Apatity, multiple arrivals can still be seen for these events.

*Fig. 10* shows the broadband  $Pn/Lg$  spectral ratio versus derived source time function for 200 events comprising the original NORESS database, the Apatity mine explosions, the Steigen aftershock series, the Puertollano events, and events from the Galilee earthquake & mining explosion database. The earthquakes in this combined data set have source time functions that range from zero (or the resolution of the data) to 1.1 seconds (a greater range than for the limited NORESS dataset). The explosions have source time functions that range from zero to 1.8 seconds. The broadband deconvolved  $Pn/Lg$  spectral ratio for the explosions is larger than for the earthquakes, and the separation between the two classes is nearly complete.

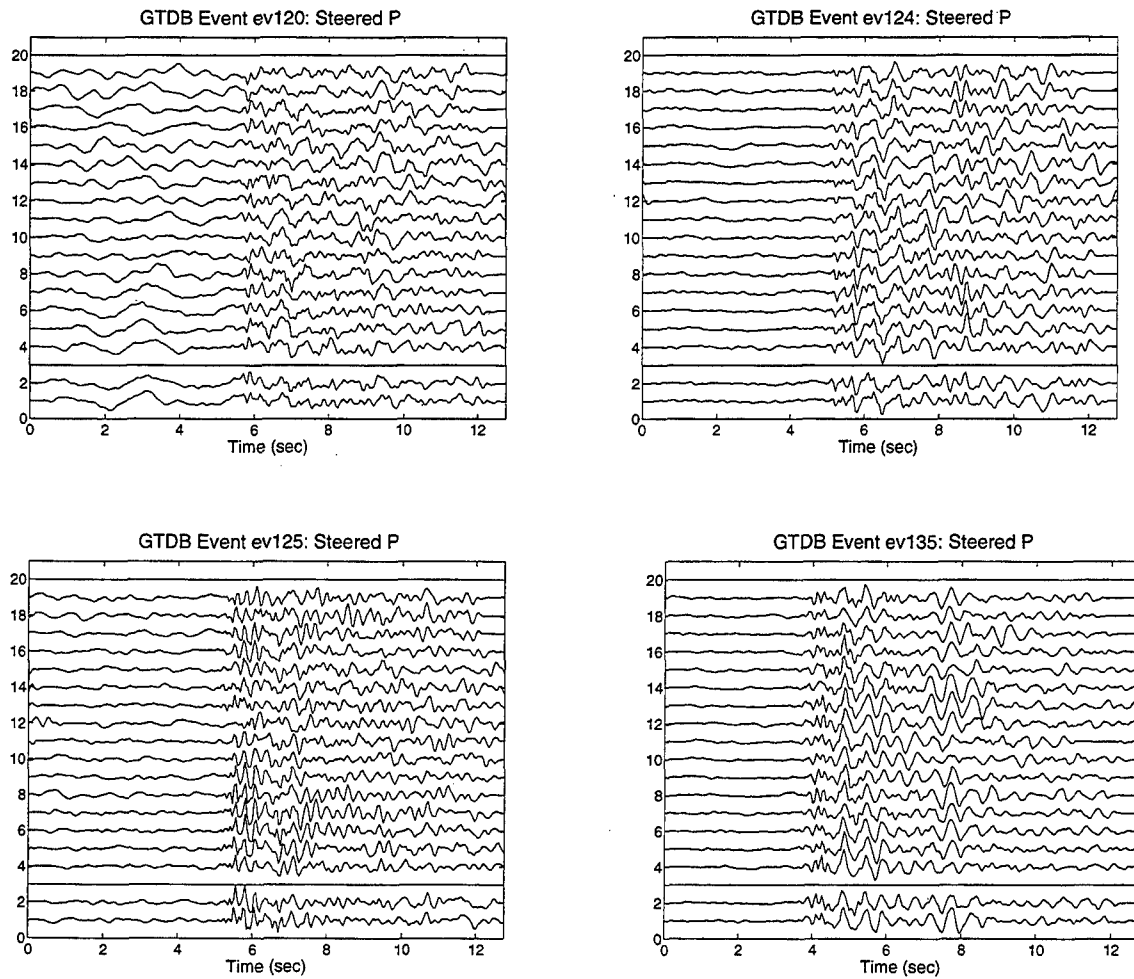


Figure 9. Steered Pn waveforms at the Sonseca array for four events from the Puertollano region.

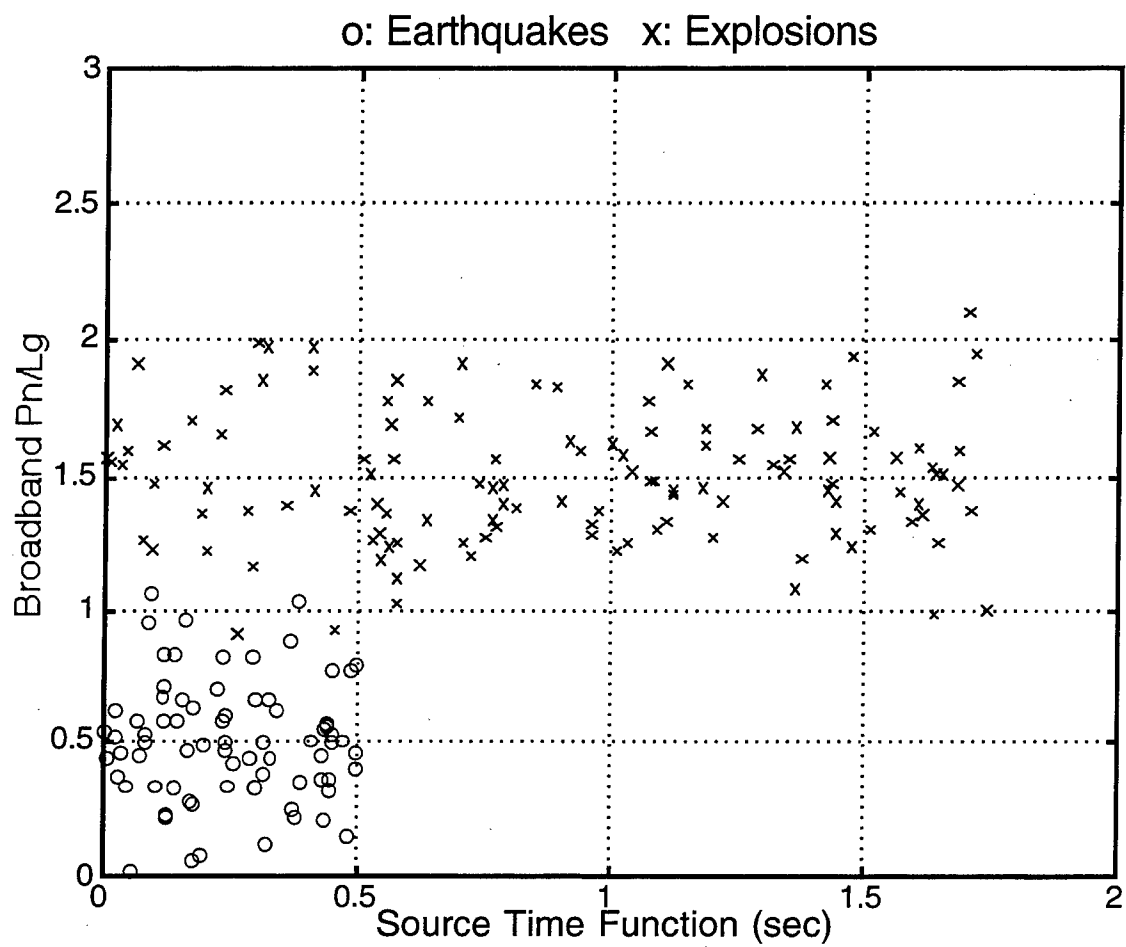


Figure 10. Broadband Pn/Lg spectral ratios after source deconvolution versus derived source time function for events at NORESS, Apatity, Steigen, Puertollano Spain, and Hormuz.

## Conclusions

We have applied a source deconvolution process to the  $Pn$  and  $Lg$  waves of small mining explosions and earthquakes in order to stabilize the spectral ratio estimates and improve discrimination capability. This stabilized spectral ratio is then used in conjunction with the derived source duration for event identification. This procedure has been tested on a number of Ground Truth Databases which include events from Scandinavia, central Europe, Spain, and the Middle East. We have found that the scatter in the spectral ratios and their parameterizations is reduced, leading to fewer misidentified events.

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